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ScienceDirect

Procedia Computer Science 44 (2015) 254 – 265

Procedia Computer Science

2015 Conference on Systems Engineering Research

"Design for Automated Assembly of Large and Complex Products: Experiences from a Marine Company Operating in Norway"

Elisabeth Lervåg Synnes[a]*, Torgeir Welo[a]

[a]*NTNU, Engineering Design and Materials, Richard Birkeland`s veg 2B, N-7491 Trondheim, Norway*

Abstract

To compete in today's global market companies must continuously improve their products and manufacturing processes. During the past several years, many Norwegian-based companies have outsourced production due to the high operational cost level. The trend is that only the production of complex, knowledge-based products which require advanced engineering, strict quality requirements and high degree of customization remains in Norway. Even for this type of products, more cost-effective product realization methods need to be established in order to strengthen overall competitiveness long term. This paper presents results from an ongoing case study done in a global marine company with operations in Norway, seeking to increase competitive advantage by improving capabilities in automation solutions for manufacturing—despite the fact that the production of large and complex products is usually regarded as particularly difficult to automate in an economical way. This paper aims to research the multifaceted challenge of moving from a manual to an automated assembly process for this type of products when this endeavor involves transferring technology from the early premature phase to full industrial implementation in parallel with the product development process. The results presented in this paper are preliminary as the technology development project is still ongoing. One of the early findings indicates that by re-designing large and complex products for handling with standard robots, the case company was able to automate assembly of its products. Furthermore, having a dedicated team enabled delivering a demonstrator after only two years by applying an *Open Innovation* approach, pulling knowledge from external experts in automation and iteratively integrating this with own organizational capabilities including technology platform, manufacturing strategy, design for manufacturing/assembly and integrated product and process development.

Peer-review under responsibility of the Stevens Institute of Technology.

Keywords: Systems Engineering; Integrated Product and Process Development; Organizational Capabilities; Technology Project; Industrialization

* Elisabeth Lervåg Synnes. Tel.: + 47 922 18 566.
E-mail address: elisler@stud.ntnu.no

Peer-review under responsibility of the Stevens Institute of Technology.
doi:10.1016/j.procs.2015.03.052

1. Introduction

To compete in a global market, companies must continuously develop new products and manufacturing processes to meet new demands from customers. There is a constant pressure to reduce costs and manufacturing locations are frequently reviewed, especially in global companies. In Norway, many companies have outsourced or relocated production to so-called low-cost countries due to high operational costs. In the short run this can give benefits in terms of lower labour costs, but it does not guarantee competitiveness in the long run. Still the production of complex products that require advanced engineering, strict quality requirements, high degree of customization and are knowledge-based tend to remain in Norway. To stay competitive in the future, more cost-effective manufacturing methods and improved technology are required even for this category of products.

Development of new technology with the introduction of, for example, rapid prototyping, advanced industrial robots, digitalization and advanced control systems may enable competitive manufacturing in which labour costs are reduced to a less significant part of the picture—sometimes less than 5% of the total. This issue is widely recognized and described in the report *Made in Norway* [1], which also refers to actions taken by governments in USA, Germany and Denmark to gain competitive advantage by development of advanced manufacturing technologies. Furthermore, in order for a company to become innovative and capable of developing improved products, towering knowledge of advanced manufacturing technologies and production processes is necessary. If production is outsourced, there is also a risk of losing competence both in manufacturing and engineering in the long run. Regaining the lost competence later is difficult, especially in the technology field with long lead time associated with competence development.

This paper addresses the problem of developing and introducing new technology in a company that is producing products in Norway. The motivation is to gain better understanding of the challenges related to introducing changes in the existing technology platform, focusing on the interplay between product design and production process. The case company, Rolls-Royce Marine (RRM), has a large, differentiated product portfolio in combination with proven capability in both ship design and system integration [2]. RRM has several production facilities located in a relatively small geographical area along the western coastline of Norway, manufacturing large and complex products at low-volume with a high degree of manual labour. This regional area is one of the few complete *maritime clusters* in the world with a vertically integrated value chain. To continuously grow the business and create new jobs, more cost-effective material flow and manufacturing methods are required. Based on this consideration, RRM has identified a need to extend their capabilities in new automation solutions for manufacturing operations, despite the fact that this type of products does not support the usual arguments for automated assembly: Firstly, automation usually requires high volume of standardized parts, whereas RRM products are typically made-to-order or engineered-to-order. Therefore, an automation system in this environment must handle mass-customization of low volumes. Secondly, product size is another factor that adds complexity.

Since RRM has limited automation experience due to its product mix, there was a need to seek competence outside the company. In addition, one could not be sure that automation of such large, complex products would be economically feasible. This resulted in a research project called Autoflex, whose goal was to develop strategies for cost-effective manufacturing of low-volume, complex and heavy products in Norway, using real time adaptive robot control to replace manual operations. A so-called "Permanent Magnet Tunnel Thruster" (TT-PM) was identified to become a suitable case fitting the project description of low volume, large and complex products. The original design of the TT-PM requires a high degree of manual labour operations. Hence, it was early on identified that automation of the existing design would not be cost efficient since it was not initially designed for automated assembly.

This paper addresses how RRM has approached the challenge of delivering a successful solution for automation of the rotor assembly by redesigning the TT-PM, pointing at lessons-learned and the challenges of going forward to industrial implementation. As a starting point, we seek to explore the following topic:

- Integration and implementation of 'new-to-the-company' type technology in product realization projects, leading to (radical) changes in existing practices and capabilities within design, process and technology. More specifically, aiming to identify the multifaceted challenges of moving from a manual to an automated assembly process for large and complex products when this endeavour involves transferring technology from the early (low readiness) phase to full industrial implementation.

This paper is organized as follows: Section 2 presents a conceptual model that we have denoted the *capability* *pyramid*, along with related theory focusing on the following topics: Integrated Product & Process Development, Design for Manufacturing, Manufacturing Strategies and Technology. Section 3 describes the case study of Automated Assembly of large and complex products in RRM. Section 4 presents Recommendations and Further Work and finally concluding remarks of the paper is presented in Section 5.

2. Theoretical background

The four-level hierarchical capability pyramid in Figure 1 depicts a visual representation of the situational description to be investigated in Section 3. Basic theory associated with each level of the pyramid will be presented below. The pyramid aims to describe the identified challenge as to how current capabilities (*Business-as-usual*) in the organization are affected when a project that involves new-to-the-company type of technology is to be introduced. Within each hierarchical level, the current capabilities must be reviewed and adapted to the technology development project—and vice-versa—before the organization arrives at a new technology capability representing the future standard. Also, each level in the pyramid must be seen in connection to each other in order to maximize the capabilities of the organization as a whole; i.e., an integrated system. For example, investing in new manufacturing processes alone will not guarantee improved performance. On the other hand, if one ensures that design is modified to the new manufacturing method and that these two levels are collectively aligned with the company's manufacturing strategy, and that the product and process are integrated and developed concurrently, then the overall capability—as represented by the company's ability to satisfy customer needs—does increase. In Figure 1, the iterative concurrent interactions between levels are represented with arrows. The more effective iteration between the different levels, the more we can optimize the organizations capability as a whole. The height of the pyramid represents the overall outcome of this optimization; if one level fails to enhance its capabilities according to the new technology, the pyramid gets lower and hence the capability becomes suboptimal.

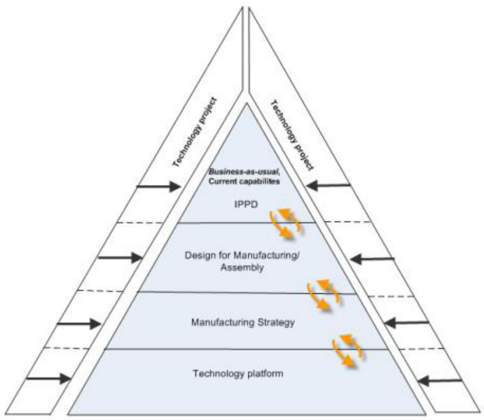


Figure 1 Capability pyramid

2.1. Integrated Product and Process Development (IPPD)

Introduction of a new product can either be done by means of existing manufacturing processes, a modified manufacturing process or it can even require a complete new manufacturing process [3]. Research indicates that up to 85% of the manufacturing costs are locked in by the product design [4, 5]. Hence, to achieve significant cost reductions in manufacturing, it is necessary to consider design and manufacturing in close connection with each other. If design and manufacturing cooperate at an early stage in the NPD (New Product Development) project, trade-offs and compromises can be made between the product and process designs to save both cost and time related to wasteful redesigns [3].

According to Department of Defense Integrated Product and Process Development Handbook [6], "*IPPD is a management technique that integrates all acquisition activities starting with requirements, definition through production, fielding/development and operational support in order to optimize the design, manufacturing, business and supportability processes*". IPPD is the concurrent, coordinated development of the product and the processes to realize a product in the market place. Further, IPPD emphasizes the use of prototypes both to demonstrate product functionality, and to demonstrate the manufacturing and service processes [7]. It may be claimed that IPPD is essentially based on the same ideas as concurrent engineering; i.e., to shorten lead time and improve quality [8, 9]. If the design is radical, however, it can be difficult to work concurrently since radical innovation is difficult to plan [10]. According to Tempelman et al. [10], definition of the manufacturing process must be done gradually and iteratively as part of the project progress. Further, as IPPD for the most aims to optimize the product and process by iterating over one design solution ('point-based') it is not given that this is the best starting point for an optimal outcome [11].

Sobek et al. [11] popularized the concept of "Set-Based Concurrent Engineering" (SBCE); i.e., considering multiple solutions and then gradually narrowing down the range of options before ending up with one final solution. The paradox of SBCE is that considering a broader range of designs, decisions are delayed compared to other companies, yet the process seems to be faster and more efficient. Hence, investing time up front ('front-loading') to explore solutions both from a design and manufacturing perspective may lead to gains in efficiency and product integration capability later in the process.

2.2. Design for Manufacture and Assembly

The theory of concurrent development of product and process includes the concepts of Design for Manufacture (DFM) and Design for Assembly (DFA). The idea is to reduce the manufacturing cost such that the design eases manufacture of the parts making up the complete product without compromising quality of the final product. Design for Assembly is a branch on the 'DFM-tree' pioneered by Boothroyd & Dewhurst [12], aiming to achieve the lowest assembly cost. This essentially means achieving an efficient assembly performed by the most suitable assembly system (manual, special-purpose machine or programmable machine assembly).

In the book Mechanized Assembly [13] Geoffrey Boothroyd & A.H Redford studied automatic assembly and recognized that the impact of designs on reducing cost was much more important than the use of mechanized assembly; considerable cost savings can be achieved by a careful consideration of the design of the product and its individual component parts.

To find out that a chosen design does not combine well with earlier decisions can be both time-consuming and complex [10]. However, by considering both manufacture and assembly at an early stage in the design process, there is an opportunity to avoid changes in the design late in the process when the cost of change is high and there is also a risk of delaying the new product in the market place. Sometimes DFM can also be rewarding to the design as the choice of manufacturing process can improve the initial design idea [10]. The principles of DFM and DFA have been of great importance in industry. It is well recognized how DFM guidelines have improved quality and reduced cost [14, 15, 16, and 17].

2.3. Manufacturing Strategies

The manufacturing strategy should support the company's competitive priorities and support the creation and selection of the organizations future operational capabilities [18, 19]. Successful decisions about automation go in line with what the company aims for in the long term, and the decisions are synchronized with the manufacturing strategy and present capabilities [20]. The Levels of Automation (LoA) concept explains and expresses the continuum of different degrees of task sharing between humans and technology, see [21]. There are several factors to consider in connection with automation of the assembly process; both under and over-automation can have negative influence on competitiveness [18]. Considering automation, each component must be analyzed in terms of shape; how to feed and orient them, material and tolerances, [22]. Up until recently, manual labour has been the preferred production method when components are technically too complicated to assembly or manufacture when the product has a short life cycle and fast market introduction is required, for customized products, and when demand is fluctuating, [23]. Further, HS&E and high risk areas for automation must be considered. Successful decisions regarding automation should be aligned with the company's long term goals, and decisions should be synchronized with the manufacturing strategy and present capabilities, [21].

2.4. Technology

In the early days of the individual companies that today is a part of RRM, products were typically designed by the designer who went down to the manual lathe or milling machine to see how to design the products for easier manufacturing. In the 1970s, Numeric Controlled (NC) machines where introduced and the programmer's role in developing programmes, making jigs and fixtures, etc. increased significantly. Today, there is a shift in that the designer again is gaining more control of the whole process by using simulation tools such as CAD/CAM/FEA, etc. The product geometry and most of the corresponding manufacturing process can be described virtually in computer models, and hence defined simultaneously. Also, programming modules can run simulations and calculate cost. This provides the opportunity to consider several scenarios and to be more confident about predicted behaviour. Further, new technology such as 3D printers and robotics enable more flexible production. The new technology may give a more seamless integration of design, product development and manufacturing, and an improved infrastructure for sharing information. However, according to Jordan et al., today's designers of complex products must consider many issues beyond the technical design challenge, and it can be difficult to develop sufficient understanding to cover all disciplines [24].

For many years, small-volume production has weighted the cost of material and labour less important than what is seen in high volume production (i.e. Toyota in the automobile industry [25]) where it is commonly justified to spend significant resources on tooling and engineering [16]. Assembly robots have been used in the manufacturing of simple products in large volumes. As many as hundred thousands or millions p.a. can be necessary to justify a fully automatic assembly operation with dedicated production equipment. Further, assembly operations are difficult to automate since the human operator is capable of many subtle manipulations, adjustments and compensations for component variation. However, the development of computer-controlled robotics during the last few years makes automatic assembly economically feasible at much lower quantities than in the past. In addition, robots have become less expensive. As robot applications are more used in the high-mix, low-volume segment, the time available to program them is reduced.

3. Case Study: Automated Assembly of Permanent Magnet Tunnel Thruster (TT-PM)

Since some specific results from this study already are available, we have chosen to denote it a case study although the study is still ongoing and therefore may be considered more of a proof-of-concept. In Section 2, a capability pyramid and theories associated with IPPD, Design for Manufacture/Assembly, Manufacturing Strategies and Technology have been presented in brief. These will now be seen in connection with efforts made in an ongoing technology project in RRM, named Autoflex. The aim is to point at the main experiences and some of the challenges implementing 'new-to-the-company' type technology, leading to changes in existing practices and capabilities. RRM wants to extend their capabilities in new automation solutions for assembly of products that are typically made-to-order or engineered-to-order. The goal is to develop a flexible, automated assembly system for products that are large and complex and do usually not call for automated assembly. Here *flexible* means a system that has reconfigurable assembly equipment, one that is scalable to fit a wide range of the product family. Further, *automated* refers to the use of robots with software that are programmed and setup to perform several operations at the same time, while taking into consideration logistics, number of interfaces and work in progress. By *complex* we mean products with a complex functionality built up by hundreds of components/parts.

3.1. Selection of product as demonstrator in Autoflex project

The Permanent Magnet Tunnel Thruster (TT-PM) is the latest tunnel thrusters design from RRM. Evaluation of technology and development of the first design and sketches started out in the early 2000s. The permanent magnet technology is new to RRM, and in 2013 RRM acquired a company with leading technology of permanent magnetised electrical machines [26]. The PM motor consists of two main parts, stator and rotor, that must be seen in connection with each other. The stator carries a number of electrical coil windings, and the rotor is fitted with strong permanent magnetised magnets. Figure 2 shows the conventional TT-PM 1600 design with a propeller diameter of 1,600 mm and a total thruster weight of more than 7,000 kg.

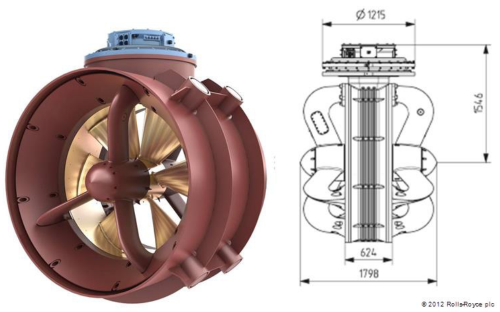


Figure 2 TT-PM 1600 conventional design built from existing technology platform [26]

TT-PM has complex functionality and strict requirements to operating life. To verify reliability of the product, experiences with a non-optimal production process was necessary to avoid introducing too many variables at once. Still this production process required knowledge about both filament winding and magnetization. The prototype/pre-series processes were labour-intensive and the magnetization process also had challenges related to HS&E. To enable competitive production of the TT-PM in Norway, this called for significantly more effective production methods moving from pre-series to product optimization. RRM also had a vision of automated production of TT-PM using robots, thus making TT-PM a suitable candidate for a demonstrator in the Autoflex project.

3.2. The Autoflex project

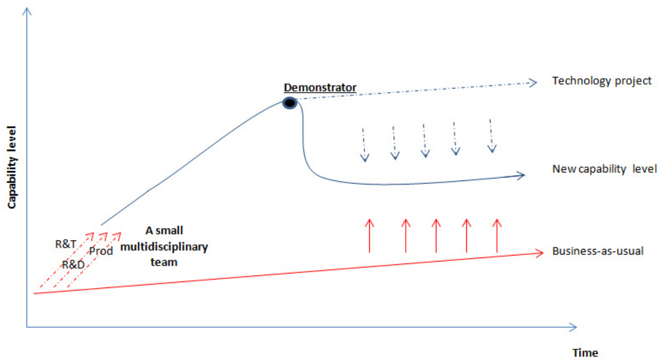
Autoflex is a project that started in 2012 with support from the external research community and collaboration with other companies (mainly experts in manufacturing and automation) as a supplement to internal RRM resources. In order to succeed with automation of the TT-PM, it was early identified that this would not be economically feasible without making significant modifications to the existing design.

A small multidisciplinary IPPD team with expertise in functionality, design for automation (external company) and RRM Engineering was assigned to make the design more suitable for automation. The existing design for automated assembly competence was limited within RRM because this capability had not been seen as crucial as complexity and volume of the existing product portfolio do not call for automated assembly. According to Leenders et al. [28] existing knowledge within an organization is often inadequate to succeed with a competitive new advantage, hence requiring high levels of creativity. Seeking competence outside the company and applying an open innovation approach [27] leveraging external resources with design for automation competence have gained the multidisciplinary competence needed. This has been of vital importance to launch a demonstrator within a period of only two years.

To ensure that the re-design was not done at the cost of efficiency and functional compromises, such as noise and vibrations, the following working method has been used: Starting with RRM requirements and related manufacturing set-up as basis, a description of how to re-design and manufacture the components was presented to design-for-automated-assembly experts who subsequently developed the process and decided which tools and equipment to be used. To ensure proposed rotor configurations to be in compliance with functional requirements, design reviews were conducted by RRM experts in permanent magnetised electrical machines. Further, weekly meetings were held to ensure that the team maintained a common understanding as iterations led to further improvements of the design.

When introducing a new product or re-designing an existing one, as the TT-PM, the team will need to make trade-offs both in terms of outcome (time-cost) and desired manufacturing methods versus product functionality [3, 10, 17, 24]. To be able to do optimal trade-offs extensive knowledge of both production process and product functionality is required. As mentioned, it took two years from the first vision of a fully automated production to launching a successful demonstrator of automated rotor assembly with the new design. According to the project manager, this illustrates the potential of developing the design of the product and production/assembly-process in parallel. However, this presumes that a multidisciplinary team has the knowledge required in terms of manufacturing process, product functionality and design for automated assembly. Further, introducing a small team that does ‘skunk work' [29] outside business-as-usual has made it possible to be creative and to do more optimal trade-offs. Figure 3 illustrates how future technology projects can be similarly organized by allowing a small team to work outside the existing boundaries of their departments to develop new capabilities. Such a small team has proven to be very efficient once people with the right skills are chosen. A technology project typically serves to stretch the organizations existing capability; the higher the peak (in Figure 3), the more radical the solution. When the technology project is ready for industrialization and ready for handover to the operational part of the organization, the findings in the technology project must be verified with a proof-of-concept demonstrator. Further development from this point requires that balance is established by multiple iterations between the team in charge of the technology project and the team running the commercial business-as-usual project. The final solution is often a compromise between current capability and the ambition level of technology projects, as illustrated in Figure 3.

Figure 3 Establishing the organizations new capability level by balancing Technology project with Business-as-usual



Since Autoflex is a technology project, it was not possible to know in advance if automated assembly of RRM products could be done with economical profit and at the same time satisfy functional requirements. A mix of people from RRM—mostly people from manufacturing and a few designers due to time and availability of resources—was also involved in the Autoflex project. It became soon clear that there was some resistance against re-designing the product mainly because the traditional design is built on a set of known principles along with RRM engineers' expertise on complex functional requirements. According to the experience gained in this project, this is one of the main challenges when only a small team is doing the re-design. According to Cheney et al. [30] one reason for resisting change is that the outcome of the proposed changes is uncertain. Therefore, an important next step will be to continuously eliminate uncertainties by using demonstrators to verify the re-design, and thus making it easier to bring the organization to the new capability level.

3.3. Results of re-designing rotor for Automated Assembly

The results to be presented in this section are related to the re-design of the rotor as the stator is still in the research phase and not ready to be demonstrated yet. The project group emphasises the need to see assembly in connection with machining. An example is dimensional accuracy of the last component due to tolerance stack-up upon assembly; this can be avoided by ensuring only one set-up in combination with a dimensional strategy for hard points on the component in machining. New technology and programming methods (combining off-line and on-line programming) allow cost effective deployment of the robotic system, which is described in Linnerud et al. [31]. Also, a flexible control system that eliminates the need for changes when introducing new products has been developed, i.e. there is no need for reprogramming between different components in the component family. Traditionally, the different paths to a product is 'hard coded' into either the PLC or robot control. This makes the solutions less flexible for changes and variations between products. Here this limitation is eliminated by creating a program that is built up with a dynamic set of rules to generate and build patterns to PLC or robot. An example of such a rule is to identify dependencies between components and establish the assembly sequence accordingly.

In the literature, several sources have shown that re-designing for automated assembly has led to cost savings in both material and machining as described in [10, 13]. In this study, one of the main changes was to re-design the components in such a way that they can be handled with standard robots. Table 1 lists some examples of design improvements to make the TT-PM more suited for automated assembly as experienced by the team.

Table 1 Re-design for automated assembly of rotor

Design for automated assembly	Conventional design	Re-design
Parts to be handled by standard robots	Not able to handle large parts with standard robots	Re-design for components to be handled by standard robots
Standardization of screw dimension (less components type to handle, one tool and one feeder)	M16 and M12	M16 replaced with several M12 (smaller bolt head solves space problem).
Bolt holes are re-designed to avoid collision with propeller blades.	Vertical bolt holes. Not enough space for torque wrench	Angular bolts to ease access for mounting tool
Reduce number of parts and operations	Dowel-pins and magnet yokes two separate parts	Dowel pins changed to be machined as part of the magnet yokes.
Simplify entering of yoke		Chamfer on the dowel-pins Force-transducer technology
Fewer feeding systems and types of components	Different design based on how many screws are needed	Standard magnet yoke design with the same amount of bolt holes. However, number of bolts that needs to be mounted varies around the propeller.
Simplify insertion		Larger entering on the dowel-pins
Conical entering to decrease need of accuracy	High demand for precision	The conical section is tighter than the clearance of the dowel pin hole so it will always enter
Reduce the need for precision. Enable use of simpler tool	Not control of component entrance	Expanding dowel-pins in connection with controlled entrance of components (force transducer and tightening in two operations)
Remove cycle-time bottle-neck	Filament winding	Encapsulation of magnets
..	..	..

3.4. Set-based approach applied to product development of large and complex products in RRM

Figure 4 is showing the concept of "*Set-based concurrent engineering*" [11] applied on business level to integrate the new technology with the existing product development in RRM; unlike Sobek et al. [11], who applied the concept on product concept level. The figure illustrates the technology project Autoflex represented with the task "Re-design for Automated Assembly of Rotor" (Table 1) on the left side. The right side represents the existing product platform and current capabilities in the company.

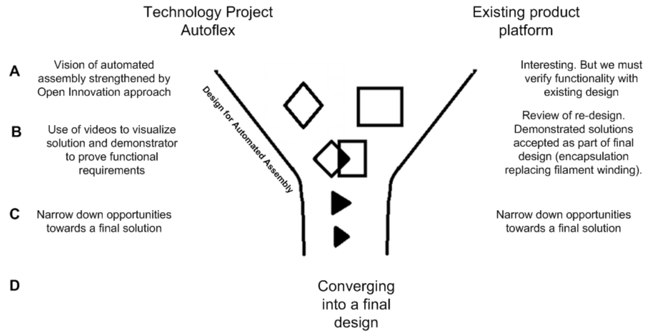


Figure 4 Set-based approach to product development of large and complex products

Sobek et al. [11] emphasize the importance of working with several sets of solutions and then gradually narrowing down ranges of options. In the RRM case, the technology project and the conventional design have been developed in parallel, which essentially means that the latter is a candidate for rejection while moving down the 'waterfall'. In the end, these two solutions will converge into one final solution. To work with two solutions in parallel in the production implementation phase is demanding, yet necessary. Firstly, the strategy serves to verify the complex functionality of the product. Secondly, since the outcome of Autoflex (phase A) was unknown from the beginning, a safe fall back is needed to meet the project time line. Re-designs must prove to fulfil functional requirements before deciding if they can be adapted as a final design, which was the case with encapsulation replacing filament winding (phase B), see Figure 4.

As emphasized by previous IPPD research [7], both demonstrators and videos have been of vital importance to 'sell' the idea/vision of a fully automated assembly of TT-PM internally and to verify how the re-design fulfil functional requirements. So far, this has enabled smooth integration with the existing product platform. In phase C, Figure 4, one continues to develop both solutions as the solutions gradually merge into an industrial solution.

The challenge of going forward includes narrowing down and converging these two solutions into one future design (product and process)—not only for TT-PM but also for future PM products (phase D). This will obviously influence all the levels in the capability pyramid that was presented in Section 2. Communication and iteration within the organization is important to ensure that the organization's capability as a whole is aligned with the final design solution. In Figure 4, the black triangle(s) represents the design as a result of merging the two solutions. How the new static organization will look like depends on which elements of the re-design in Autoflex that will be incorporated as part of the future conventional design, especially since the outcome of the ongoing re-design of stator solution (part D) is unknown at the moment.

4. Recommendations and Further Work

As illustrated in Figure 5, the outcome of the Autoflex project will form the basis for future guidelines for automated assembly handed over to support R&T (Research & Technology) and R&D (Research & Design). These design guidelines must be seen in connection with Manufacturing Strategy, Technology platform, as well as existing and future capabilities.

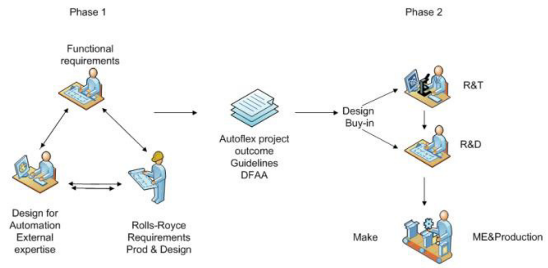


Figure 5 Autoflex guidelines for future capabilities

The successful development (Phase 1) of a rotor assembly demonstrator has shown that the automated assembly of the rotor is feasible. The next challenge (Phase 2) is to incorporate knowledge and best-practices established through the Autoflex project in the design of TT-PM, as well as future PM products and technology/development projects in general. In particular, this will be a challenge for the TT-PM case, where a small team has introduced radically new designs seen in relation to the existing pre-series design. The technology project has given the company insight into what can be achieved, providing a valuable input to resource and technology investments in the future (from Phase 1 to Phase 2). For example, should the design be done for a special type of robot or, alternatively, be made applicable to a general design and rather have the robot adapting to the design?

A strategy for automation and level of automation (LoA) should be in place, as emphasized by Frohm [21], together with a committed ambition level aligned with production, requirements and demands. Examples of such an ambition could be to design all bolt configurations so that they can be mounted with a robot. The next level would be to design the rotors to be assembled by robots, and the higher ambition level of having no manual assembly of PM products. Deciding on the correct level of automation requires knowledge of automation and what is possible and what is not. Gaining the necessary competence of what is possible comes at a price, though. The question is whether or not to pay the price required for gaining the necessary knowledge. In this particular case, it has proven to be beneficial to invite in external competence to support this project and combine internal RRM product expertise with external expertise in automated assembly. This has resulted in an automated rotor assembly that satisfies the criteria's of HSE, reduction in manual work, Lean production and reduced work in progress after only two years.

4.1. Future capabilities in R&T and R&D department

The Autoflex project has enabled vision programming and configuration directly from the CAD model. This provides more flexibility with regards to size and number of parts. To optimize further, one should look for opportunities for the use of common parts, as well as design parts for use of common production tools in the development of the complete TT-PM range. When exploring automated assembly, one should also consider the opportunities for standardization along with product platforms. Introducing robots and automated assembly will not change the existing design process. However, designers must consider guidelines for automated assembly, e.g. knowing which robot to design for. If a flexible production is utilised to make more project specific designs of the rotor, existing working methods will have to change. In general, one will need to focus more on parameterization and design automation. This is possible but requires more advanced use of CAD and other tools as well as the functions that support the capture and re-use of design intent and user intelligence.

5. Conclusion

To enable competitive production of the TT-PM in Norway, a technology project named Autoflex was defined to develop more effective production methods—i.e., automate assembly—while moving from pre-series to product optimization. Introducing 'new-to-the-company' type technology in product realization projects is a major challenge since it enforces the company's existing capabilities to change. This is particularly difficult when critical product functionalities must be validated simultaneously as the production technology, which was the case for the new TT-PM design considered herein. Therefore, exploration activities within the technology project have to run in parallel with exploitation activities within the existing product platform, since the outcome of the Autoflex project was uncertain and a fall-back solution was needed to manage risk.

A small IPPD team with the necessary expertise has been assigned to make the design more suitable for automation. Re-designing for automated assembly has led to savings in both material and machining, supporting the findings described in [10, 13]. Applying an open innovation approach [27] by leveraging external resources with towering design-for-automation competence has been of vital importance to achieve a demonstrator within a period of two years only. During this process, weekly meetings were held to ensure that re-design was not done at the cost of efficiency and functional compromises, such as noise and vibrations, for the TT-PM. The combination of the team-members' knowledge and capabilities is what creates new knowledge and insights [28], which proved to be essential to make necessary trade-offs to maintain acceptable risk levels as seen from a business perspective.

The technology project has proven that automated assembly of large and complex products is feasible when effectively combining proven technology and suitable design concepts. From an economical point of view, however, the key is to re-design the product for the manufacturing process employed; examples of such design modifications include part handling with standard robots, enabling tools to get access where needed, standardization of bolt configurations, reduced need for precision by using expanding dowel-pins, and in-process force-transducer technology.

Technology projects typically serve to stretch the organization's existing capability and can thus be considered as *radical* by the rest of the organization. Here, prototypes or demonstrators are important artefacts to verify that results are not achieved at the cost of functional requirements or any other compromises that degrade the value of the product as perceived by the customer. This will also help overcome internal resistance towards change [30]. The resulting outcome of a project is usually a compromise between the existing capability and the ambition level of technology projects, as illustrated by the simple model in Figure 3 above.

By developing new technology in parallel with an existing product platform, complex functional requirements can be verified at the same time as the establishment of an optimal manufacturing process concept for industrial implementation. The process of converging into one final successful design from the sets of different options is largely dependent on inter and intra organizational communication strategies. These must ensure that the organizational capability as a whole is aligned with the requirements of the final design as represented by the needs of the customer as well as intermediate (internal) customers and stakeholders. This process is particularly demanding, yet necessary, and will impact all four hierarchical levels in the capability pyramid model presented in Section 2.

Acknowledgements

We would like to express our thanks to the involved parties in the Autoflex project for the support and valuable inputs provided to our work. We particularly thank Rolls-Royce Marine for allowing us to get insight into the development process of TT-PM. This work has been financed by Rolls Royce Marine and the Research Council Norway, who are both gratefully acknowledged.

References

1. Fixdal, J., 2013. *Made in Norway? Hvordan roboter, 3D-printere og digitalisering gir nye muligheter for norsk industri*, Oslo: Teknologirådet.
2. Rolls-Royce, p., 2014. *Marine History: Rolls-Royce.* [Online]
Available at: http://www.rolls-royce.com/marine/about/marine_history/index.jsp
[Accessed 15 May 2014].
3. Swink, M., Talluri, S. & Pandejpong, T., 2006. Faster, better, cheaper: A study of NPD project efficiency and performance tradeoffs. *Journal of Operations Management,* Volume 24, pp. 542-562.
4. O`Driscoll, M., 2002. Design for Manufacture. *Journal of Materials Processing Technology,* 122(2-3), pp. 318-321.
5. Dewhurst, B., 2012. *Boothroyd Dewhurst, Inc.* [Online]
Available at: http://www.dfma.com/software/dfa.htm
[Accessed 18 September 2014].
6. Defense, D. o., 1998, p.2. *DoD Integrated Product and Process Development.* Washington, DC: Office of the under secretary of defense (acqusition and technology).
7. Jordan, J. & Michel, F. J., 2000. *Next generation Manufacturing: Methods and Techniques.* s.l.:John Wiley & Sons.
8. Winner, R. i. f. D. A., 1988. *The Role of Concurrent Engineering in Weapons System Acquisition.* Institute for Defense Anlyses United States: Institute for Defense Analysis.
9. Ottosson, S., 2004. Dynamic product development - DPD. *Technovation,* 24(3), pp. 207-217.
10. Tempelman, E., Shercliff, H. & van Eyben, B., 2014. *Manufacturing and Design.* 1st ed. Oxford, UK: Elsevier Ltd.

11. Sobek, D. K., Ward, A. C. & Liker., J. K., 1999. Toyota`s Principles of Set-Based Concurrent Engineering. *MITSloan,* 40(2), pp. 67-83.
12. Boothroyd, G. & Dewhurst, P., 1983. *Product Design for Assembly A designer`s Handbook.* University of Massachussets: Deparment of Mechanical Engineering.
13. Boothroyd, G. & Redford, A., 1968. *Mechanized assembly. Fundamentals of parts, feeding, orientation, and mechanized assembly.* 1st ed. New York: McGraw-Hill.
14. Hoque, A., Halder, P., Parvez, M. & Szecsi, T., 2013. Integrated manufacturing features and Design-for-manufacture guidelines for reducing product cost CAD/CAM envrionment. *Computers & Industrial Engineering,* 66(4), pp. 988-1003.
15. Kuo, T., Huang, S. & Zahng, H., 2001. Design for manufacture and design for "X": concepts, applications, and perspectives. *Computers & Industrial Engineering,* 41(3), pp. 241-260.
16. Bralla, J., 1999. *Design for Manufacturability Handbook.* 2nd ed. New York: McGraw-Hill.
17. Ulrich, K. & Eppinger, S., 2012. *Product Design and Development.* 5th ed. New York: McGraw-Hill Irwin.
18. Säfsten, K., Winroth, M. & Stahre, J., 2007. The content and process of automation strategies. *International Journal of Production Economics,* 110(1-2), pp. 25-38.
19. Hayes, R. & Pisano, G., 1994. Beyond World-Class: The New Manufacturing Strategy. *Harward Business Review,* pp. 77-86.
20. Lindström, V. & Winroth, M., 2010. Aligning manufacturing strategy and levels of automation: A case study. *Journal of Engineering and Technology Management,* 27(3-4), pp. 148-159.
21. Frohm, J., 2008. *Levels of Automation in Production Systems.* Gøteborg, Sweden: Chalmers University of Technology, Phd Dissertation No. 2736, Department of Production and Production Developmen
22. Boothroyd, G., Dewhurst, P. & Knight, W., 2011. *Product Design for Manufacture and Assembly.* 3rd ed. s.l.:CRC Press Taylor & Francis Group.
23. Groover, M., 2007. *Automation, Production Systems, and Computer-Integrated Manufacturing.* 3rd ed. NJ USA: Prentice Hall Press.
24. Price, M., Raghunathan, S. & Curran, R., 2006. An integrated systems engineering approach to aircraft design. *Progress in Aearospace Sciences,* 42(4), pp. 331-376.
25. Shingo, S., 1989. *A study of the Toyota Production System.* 1st ed. New York: Productivity Press.
26. Rolls-Royce, p., 2014. *Fact sheet Tunnel Thruster PM.* [Online]
Available at: http://www.rolls-royce.com/Images/RR_B_Fact%20sheet_TT-PM%201600_0812_tcm92-51007.pdf
[Accessed 23 Oct 2014].
27. Chesbrough, H., 2003. *Open Innovation The New Imperative fir Creating and Profiting from Technology.* 1st ed. Boston, Massachusetts: Harvard Business School Press.
28. Leenders, R., Van Engelen, J. & Kratzer, J., 2003. Virtuality, communication, and new product team creativity: a social network perspective. *Journal of Engineering and Technology Management,* 20(1-2), pp. 69-92.
29. Rich, B. & Janos, L., 1994. *Skunk Works- A personal Memoir of My Years at Lockheed.* 1st ed. New York: Little, Brown and company.
30. Cheney, G., Christensen, L., Jr., Z. & T.E. Ganesh, S., 2004. *Organizational Communication in an Age of Globalization Issues, Reflections, Practices.* 1st ed. Long Grove, Illinois: Waveland Press, Inc..
31. Linnerud, Å. et al., 2009. Safe Assembly of Low Volume Complex Products. *Journal of Advanced Manufacturing Technology,* Volume 45, pp. 999-1006.